Femoral nerve excursion with knee and neck movements in supine, sitting and side-lying slump

Sierra-Silvestre, Eva; Bosello, Francesca; Fernández-Carnero, Josué; Hoozemans, Marco J.M.; Coppieters, Michel W.

published in
Musculoskeletal Science and Practice
2018

DOI (link to publisher)
10.1016/j.msksp.2018.06.007

document version
Publisher's PDF, also known as Version of record

document license
Article 25fa Dutch Copyright Act

Musculoskeletal Science and Practice 37 (2018) 58–63

Contents lists available at ScienceDirect

Musculoskeletal Science and Practice

journal homepage: www.elsevier.com/locate/msksp

Original article

Femoral nerve excursion with knee and neck movements in supine, sitting and side-lying slump: An *in vivo* study using ultrasound imaging

Eva Sierra-Silvestre[a,b,c,*], Francesca Bosello[a], Josué Fernández-Carnero[b], Marco J.M. Hoozemans[a], Michel W. Coppieters[a,d,e]

[a] *Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam Movement Sciences, Amsterdam, The Netherlands*
[b] *Department of Physical Therapy, Occupational Therapy, Rehabilitation and Physical Medicine, Rey Juan Carlos University, Madrid, Spain*
[c] *Physiotherapy, School of Allied Health Sciences, Griffith University, Gold Coast, Australia*
[d] *Menzies Health Institute Queensland, Griffith University, Gold Coast, Australia*
[e] *Physiotherapy, School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane, Australia*

ARTICLE INFO

Keywords:
Neuropathy
Neuropathic pain
Neurodynamics
Sonography

ABSTRACT

Background: Neurodynamic assessment and management are advocated for femoral nerve pathology. Contrary to neurodynamic techniques for other nerves, there is limited research that quantifies femoral nerve biomechanics.
Objectives: To quantify longitudinal and transverse excursion of the femoral nerve during knee and neck movements.
Design: Single-group, experimental study, with within-participant comparisons.
Methods: High-resolution ultrasound recordings of the femoral nerve were made in the proximal thigh/groin region in 30 asymptomatic participants. Scans were made during knee flexion in supine and a semi-seated position, and during neck flexion in side-lying slump (Slump $_{\text{FEMORAL}}$). Healthy participants were assessed to reveal normal nerve biomechanics, not influenced by pathology. Data were analysed with one-sample and paired t-tests. Reliability was assessed with intraclass correlation coefficients (ICC).
Results: Longitudinal and transverse excursion measurements were reliable (ICC ≥ 0.87). With knee flexion, longitudinal femoral nerve excursion was significant and larger in supine than in sitting (supine (mean (SD)): 3.6 (2.0) mm; $p < 0.001$; sitting: 1.1 (1.6) mm; $p = 0.001$; comparison: $p = 0.001$). There was also excursion in a medial direction (supine: 1.4 (0.3) mm; $p < 0.001$; sitting: 0.7 (0.6) mm; $p < 0.001$) and anterior direction (supine: 0.2 (0.2) mm; $p < 0.001$; sitting: 0.1 (0.2) mm; $p = 0.06$). Neck flexion in Slump $_{\text{FEMORAL}}$ did not result in longitudinal (0.0 (0.3) mm; $p = 0.55$) or anteroposterior (0.0 (0.1) mm; $p = 0.10$) excursion, but resulted in medial excursion (1.1 (0.5) mm; $p < 0.001$).
Conclusion: Although the femoral nerve terminates proximal to the knee, femoral nerve excursion in the proximal thigh occurred with knee flexion; Neck flexion in Slump $_{\text{FEMORAL}}$ resulted in medial excursion.

1. Introduction

Neurodynamics is a clinical concept that uses movement (1) to assess increased mechanosensitivity of the nervous system; and (2) to restore the altered homeostasis in and around the nervous system (Coppieters and Nee, 2015). Anatomical and biomechanical studies support the biological plausibility of upper limb neurodynamic tests (ULNTs) (Nee et al., 2012) and common neurodynamic tests for the lower limb, such as the straight leg raise test (Coppieters et al., 2015a,b; Rade et al., 2017; Ridehalgh et al., 2015) and slump test (Coppieters et al., 2005; Ellis et al., 2016; Shacklock et al., 2016). There are however few biomechanical studies which evaluate the neurodynamic tests for the femoral nerve.

The 'Prone Knee Bend' test and the 'Side-lying Slump Knee Bend' test (or Slump $_{\text{FEMORAL}}$) have been suggested to assess increased mechanosensitivity of the femoral nerve (Butler, 2000). As the name indicates, in the Prone Knee Bend test, the patient's knee is flexed while lying in prone. The addition of hip extension is commonly suggested to further elongate the femoral nerve bedding (Butler, 2000). There are preliminary intra-operative data from a case series of four patients with

* Corresponding author. Physiotherapy, School of Allied Health Sciences, Griffith University, Gold Coast, Australia.
E-mail addresses: @esiesil, eva.sierrasilvestre@griffithuni.edu.au (E. Sierra-Silvestre), @Josuefisio (J. Fernández-Carnero), @michelcoppie (M.W. Coppieters).

https://doi.org/10.1016/j.msksp.2018.06.007
Received 6 February 2018; Received in revised form 3 June 2018; Accepted 20 June 2018

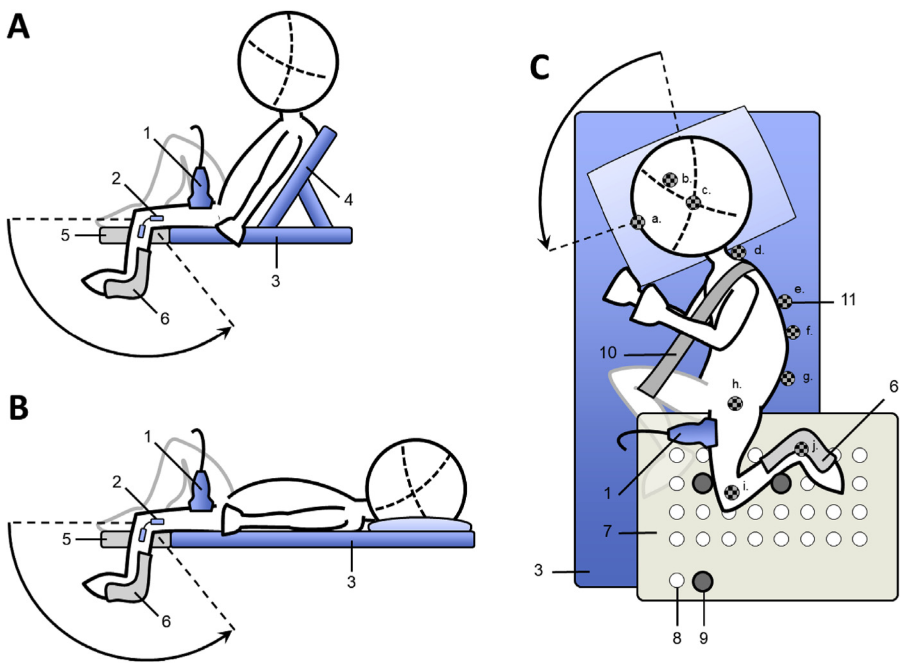

Fig. 1. Experimental set-up for the (A) semi-seated position; (B) Supine; and (C) Slump $_{\text{FEMORAL}}$. 1. Ultrasound probe; 2. Knee electrogoniometer; 3. Plinth; 4. Back support; 5. Foot support (right leg); 6. Ankle orthosis; 7. Pegboard (0.9 × 1.1 m) to support left leg; 8. Illustration for empty holes in pegboard; 9. Illustration for mechanical stop in pegboard to position left leg; 10. Fixation belt to maintain slumped position; 11. Movement analysis markers (a. Tip of nose; b. Side of the head (temple); c. Tragus; d. C7; e. T9; f. T12; g. L4; h. Left greater trochanter; i. Left lateral condyle of the femur; j. Left lateral malleolus. A digital compact camera (Powershot G7 X, Canon Inc., Japan) was placed on a frame above the left hip. Pictures were taken at the start and end position of each manoeuvre. Although unlikely that the ankle position would have influenced femoral nerve biomechanics, an orthosis was applied to the left ankle to maintain the ankle in zero degrees during the experiment.

a L3–L4 disc herniation that a manoeuvre similar to the Prone Knee Bend test results in nerve root movement (mean (SD): ~3.8 (0.5) mm) and a reduction in intraradicular blood flow (Kobayashi et al., 2003). However, differential diagnosis or structural differentiation between neural and non-neural structures is difficult with this test. To address this issue, the Slump $_{\text{FEMORAL}}$ was developed to allow for structural differentiation (Butler, 2000). Slump $_{\text{FEMORAL}}$ is performed in side-lying, and combines knee flexion and hip extension, with full spinal flexion. The addition of spinal flexion gives Slump $_{\text{FEMORAL}}$ suggested superiority over the standard Prone Knee Bend test (Trainor and Pinnington, 2011), as the mechanical loading of the nervous system is larger and neck extension can be used for structural differentiation when the test reproduces the patient's back and/or leg pain (Butler, 2000).

There is however a lack of biomechanical data which quantify the biomechanical effects of knee flexion on the femoral nerve, and of neck movements in the end position of Slump $_{\text{FEMORAL}}$. The primary aims of this paper were therefore (1) to determine whether knee flexion leads to longitudinal and transverse excursion of the femoral nerve; and (2) to analyse the effect of neck movement in Slump $_{\text{FEMORAL}}$ on femoral nerve excursion.

2. Materials and methods

2.1. Participants

Thirty healthy volunteers participated in the study (mean (SD) age: 25.7 (2.9) years; body height: 172.1 (9.7) cm; body weight: 67.5 (10.5) kg; 15 women). In agreement with previous studies (Coppieters et al., 2009; Coppieters et al., 2015a,b), we selected healthy participants rather than patients with nerve pathology, as our intent was to reveal normal nerve biomechanics. The sample size was calculated *a priori* using G*Power software (Version 3.1.7, University of Düsseldorf, Germany) (Faul et al., 2007) to detect longitudinal nerve excursion with knee and neck movement. To obtain 80% statistical power (1-β error probability) with an α-error level probability of 0.05 and an effect-size of 0.5, the estimated number of required participants was 28. Data collection was conducted between February and May 2017.

Participants had to be at least 18 years old, pain and symptom free in relevant regions (i.e., leg, trunk and neck) at the time of the evaluation, with no history of pain or dysfunction for which treatment was sought in the 3 months preceding the study, and no history of surgery or other known relevant conditions such as diabetes and other systemic conditions. Screening tests for hip, knee and spine range of motion (ROM) and muscle strength were performed, and patients were excluded if abnormalities were identified. Two additional participants were recruited, but excluded due to the inability to obtain sufficiently high-quality ultrasound video clips of the femoral nerve during knee movements due to lateral movement of the nerve out of the ultrasound plane.

The Scientific and Ethical Review Committee at X approved the study and all participants provided written informed consent before commencing the study.

2.2. Femoral nerve anatomy

The femoral nerve is the main branch of the lumbar plexus (L2-L4). The nerve runs through the fibres of the psoas major and descends in the canal formed between the psoas and iliacus muscles. The femoral nerve passes under the inguinal ligament, lateral to the femoral artery and anterior to the flexion-extension axis of the hip, to reach the thigh. Approximately 1–4 cm distal to the inguinal ligament, the nerve splits in anterior and posterior divisions. The anterior division supplies the sartorius muscle; the posterior division supplies the quadriceps. Anterior cutaneous branches from the anterior division provide sensation to the anterior and inner thigh. The saphenous nerve branches of the posterior division and is a sensory nerve which runs posterior to the flexion-extension axis of the knee. Its infrapatellar branch innervates the skin over the patella and the other branches innervate the skin of the medial side of the leg and foot. The femoral nerve ends proximal to the knee, whereas the saphenous nerve continues to the foot.

2.3. Manoeuvres

1) Knee flexion in supine and semi-seated position

Knee flexion of the left leg was performed while the participant was in a (1) supine position (hip: ~0°) and (2) semi-seated position with the trunk supported by a back-rest (hip flexion: ~40°) (Fig. 1 A&B). The posterior thigh rested on the plinth, with the lower leg outside the plinth (~5 cm over the edge of the plinth). The right leg was in hip and knee flexion with the foot resting on a small platform, positioned at the level of the plinth. The order of knee flexion in either supine or the semi-seated position was randomised.

2) Neck flexion in Slump $_{\text{FEMORAL}}$

With the participant in side-lying slump with the left hip in extension and the left knee in flexion, neck flexion was added (Fig. 1C). Neck movements in the end-position of Slump $_{\text{FEMORAL}}$ are commonly used sensitising manoeuvres to structurally differentiate whether the symptoms have a neural or non-neural (e.g., muscular or articular) origin (Trainor and Pinnington, 2011).

Each manoeuvre was repeated three times for longitudinal excursion and three times for transverse excursion, with 30s rest between repetitions. Consistent with other studies (Coppieters et al., 2009; Coppieters et al., 2015a,b), movements were within comfortable ranges of motion, and differences in knee and neck ROM were allowed between participants. However, within each participant, the ROM remained the same for the different manoeuvres. The available ROM was also determined by the amount of lateral nerve movement, as this causes the nerve to move outside the ultrasound plane.

2.4. Movement assessment and position control

Movement of the knee and neck were recorded in order to move through the same ROM for the three repetitions within and between conditions. The position of the spine and hip were controlled during Slump $_{\text{FEMORAL}}$ to limit the joint movements to the knee and neck manoeuvres.

1) Knee flexion in supine and semi-seated position

Knee movements were measured throughout the ROM using a twin-axis electrogoniometer (SG150; Biometrics Ltd, Newport, UK). Calibration was performed in each participant using a standard digital goniometer. The electrogoniometer was sampled at 100 Hz (Spike2 software, Version 6.06, Power 1401 data acquisition system; Cambridge Electronic Design, Cambridge, UK). The signal was filtered post-hoc using a Butterworth 3rd order filter to reduce noise and was synchronised with the ultrasound video clips. The hip position was measured with a digital goniometer (Powerfix, Germany) at the start and end of each manoeuvre.

2) Neck flexion in Slump $_{\text{FEMORAL}}$

The participants lay on their right side. They were asked to hold their right leg and to “cuddle up to it” so that the right thigh was close to their chest. Straps maintained the right hip and trunk in flexion. A custom-built pegboard (0.9 m × 1.1 m) was used to position the left leg into knee flexion and hip extension (Fig. 1C). Digital photos of the start and end positions were made to compare the location of 10 reflective markers to evaluate movement and positions of relevant segments. The camera (Powershot G7 X, Canon Inc., Japan) was mounted on a frame ~2 m above the plinth. To measure neck movements, two vectors were defined by markers on the head and trunk. Hip movements were measured using markers on the trunk and thigh, and knee movements by using markers on the thigh and lower leg. Joint angles were calculated using a custom-written MATLAB program.

2.5. Longitudinal and transverse nerve movement

2.5.1. Ultrasound system

Longitudinal and transverse excursion of the femoral nerve was visualised using ultrasound (Model HM70A, Samsung, South Korea). The transducer (12 MHz linear array LA3-16AD, Samsung, South Korea) was attached to a custom-made mechanical arm to assist in the positioning of the transducer. B-mode real-time ultrasound imaging was used with an image resolution between 8.8 and 9.8 pixels/mm. Frequency was set at 6.8 MHz and ultrasound videos clips were recorded at 36 frames/s, which was downsampled to 12 frames/s in the analysis to improve the accuracy of the correlation algorithm for tissues moving at low velocities (Dilley et al., 2001). All scans were performed by the same investigator (ESS), a physiotherapist who underwent ultrasound imaging training prior to commencing the study (e.g., via a 3 EC course in Musculoskeletal Imaging, including 30 h of ultrasound practicals, and via ~50 h of supervised and independent training in scanning the femoral nerve in the groin region).

2.5.2. Identification of the femoral nerve

To visualise the femoral nerve, we slightly modified the method described by Fanara et al. (2014) and Szucs et al. (2010). First, the anterior superior iliac spine was located by palpation and the transducer was positioned over this bony landmark. The transducer was then moved caudally until the anterior inferior iliac spine was reached; and then moved medially until the femoral vein and artery were visualised. The femoral nerve is located lateral to the femoral artery, and has an oval or triangular honeycomb appearance (Gruber et al., 2003). The transducer was then moved proximally to verify that the nerve had not yet split. With the transducer, just below to the inguinal ligament, and with a cross-sectional view of the femoral nerve, transverse nerve excursion was recorded. The transducer was then rotated 90° and aligned with the course of the femoral nerve to evaluate longitudinal excursion.

2.5.3. Data analysis

For longitudinal excursion, ultrasound video clips were recorded. Each clip was converted to a sequence of separate images and analysed using custom-written MATLAB software (The MathWorks, Inc, Natick, Massachusetts). A cross-correlation algorithm was used to measure the motion of the speckle features in selected regions of interest between adjacent frames of the image sequence (Dilley et al., 2001). The femoral nerve and a bony landmark on the femur in the vicinity of the nerve were tracked (3 regions of interest per structure).

For transverse excursion, the position of the femoral nerve relative to the femur was determined from cross-sectional ultrasound images taken at the start and end position of each repetition for each manoeuvre, using ImageJ software (National Institutes of Health, Bethesda, Maryland, USA). The perimeter of the nerve was traced manually and the centroid of the nerve was then calculated automatically (X,Y coordinates). The coordinates of the centroid from the last frame were subtracted from the coordinates from the first frame to calculate mediolateral and anteroposterior displacement (Boyd et al., 2012; Ridehalgh et al., 2015). Coordinates were also determined for a landmark on the femur (apex of the femoral head).

To correct for possible movement of the ultrasound transducer, the movement of the femur was subtracted from the movement of the nerve to calculate the longitudinal and transverse excursion of the femoral nerve.

2.5.4. Reliability

Although we have previously shown high reliability for comparable measurements (Coppieters et al., 2015a,b), we conducted a limited reliability study. We verified the intra-tester reliability for the calculation of longitudinal and transverse nerve movement associated with knee flexion in supine. The main reason to conduct this reliability analysis was the absence in the literature of data on the reliability of the measurement of femoral nerve excursion.

In 10 consecutive patients, longitudinal and transverse nerve excursion was quantified for three repetitions of knee flexion while the participant was in supine. The same ultrasound video clips (longitudinal excursion) and images (transverse excursion) were analysed twice in a de-identified fashion on two consecutive days. The reliability was verified by calculation of the Intraclass Correlation Coefficient

($ICC_{(2,1)}$) and Standard Error of Measurement (SEM = SD x √(1-ICC) (Weir, 2005)).

2.6. Statistical analysis

The assumption of normality was checked by a Shapiro-Wilks test and appeared not to be violated. Therefore, mean (SD) and frequencies are reported. One-sample t-tests were performed to determine whether the amount of longitudinal and transverse nerve movement in supine, semi-seated and Slump $_{\text{FEMORAL}}$ was different compared to no nerve movement. Paired t-tests were conducted to compare whether longitudinal and transverse nerve movement differed between supine and the semi-seated position. Paired t-tests were also used to evaluate joint movement and position control between start and end positions. Pearson's r was determined for all t-tests as a measure of the effect size. The level of significance was set at $p < 0.05$. All statistical procedures were performed in IBM SPSS statistics (Version 20, IBM Corp, Armonk, NY, USA).

3. Results

3.1. Reliability of nerve excursion

The measurements of longitudinal and transverse femoral nerve movement were reliable (Longitudinal excursion: $ICC_{(2,1)}$: 0.87 (95%CI: 0.69–0.96); SEM: 0.84 mm; Transverse excursion along X-axis (i.e., medio-lateral): $ICC_{(2,1)}$: 0.87 (95%CI: 0.47–0.97); SEM: 0.09 mm; Transverse excursion along Y-axis (i.e., anterior-posterior): $ICC_{(2,1)}$: 0.97 (95%CI: 0.87–0.99); SEM: 0.03 mm). Because the reliability was high and in line with a recent review (Kasehagen et al., 2017), reliability will not be discussed further in this manuscript.

3.2. Movement assessment and position control

ROM (mean (SD)) for knee flexion was 129.9 (6.9) degrees in supine and 131.9 (6.9) degrees in the semi-seated position. The range of knee motion was not different for the two conditions ($p = 0.34$). The mean (SD) range of neck movement during Slump $_{\text{FEMORAL}}$ was 94.0 (12.6) degrees (Table 1).

The position of the other segments was successfully controlled in supine, the semi-seated position and Slump $_{\text{FEMORAL}}$. The mean differences in position were negligible (≤0.2°) and not significant (Table 1).

3.3. Femoral nerve excursion with knee flexion

Knee flexion was associated with longitudinal excursion of the femoral nerve in the distal direction relative to the femur (supine (mean (SD)): 3.6 (2.0) mm; $p < 0.001$, $r = 0.79$; semi-seated: 1.1 (1.6) mm; $p = 0.001$, $r = 0.44$) (Table 2 & Fig. 2A). Longitudinal nerve excursion was greater in supine than in the semi-seated position (mean difference (SD): 2.5 (2.5) mm; $p < 0.001$, $r = 0.57$).

Knee flexion also resulted in a transverse excursion of the femoral nerve, namely in a medial direction (supine (mean (SD)): 1.4 (0.3) mm; $p < 0.001$, $r = 0.8$; semi-seated: 0.7 (0.6) mm; $p < 0.001$, $r = 0.4$) and anterior direction (supine: 0.2 (0.2) mm; $p < 0.001$, $r = 0.3$; semi-seated: 0.1 (0.2) mm; $p = 0.06$, $r = 0.2$) (Table 2 & Fig. 2B). Transverse excursion was significantly larger in supine than in the semi-seated position in the anterior direction (mean difference (SD): 0.7 (0.7) mm; $p < 0.001$, $r = 0.6$) and medial direction (0.2 (0.3) mm; $p = 0.006$, $r = 0.3$).

3.4. Femoral nerve excursion with neck movement in slump $_{\text{FEMORAL}}$

Neck flexion in Slump $_{\text{FEMORAL}}$ was not associated with longitudinal excursion of the femoral nerve in the proximal thigh (mean (SD): 0.0 (0.3) mm; $p = 0.55$; $r = 0.11$). However, the femoral nerve moved medially (mean (SD): 1.1 (0.5) mm; $p < 0.001$, $r = 0.6$) with neck flexion, but not in anteroposterior direction (0.0 (0.1) mm; $p = 0.10$, $r = 0.07$) (Table 2 & Fig. 2A&B).

4. Discussion

The main findings of this study were that, when assessed in healthy participants, (1) the femoral nerve at the groin region moved predominantly in a distal, but also medial and superficial direction during knee flexion; and (2) neck flexion in Slump $_{\text{FEMORAL}}$ did not result in longitudinal excursion of the femoral nerve, but was associated with nerve movement in a medial direction.

In supine, the magnitude of longitudinal excursion of the femoral nerve with knee flexion was 3.6 (2.0) mm. This is substantial considering the distance between the location of the joint movement (knee) and the location of the measurement (groin), and the fact that the femoral nerve ends proximal to the knee. Most plausibly, longitudinal nerve movement is induced by distal movement and elongation of the quadriceps, and skin and fascia of the anterior thigh. Although there are no biomechanical data available, knee flexion might also load the infrapatellar branches of the saphenous nerve, and thus indirectly influence femoral nerve biomechanics via the saphenous nerve. We believe however that the impact on the distal excursion of the femoral nerve observed in this study would be minimal. After all, the saphenous nerve runs posterior to the flexion-extension axis of the knee, and knee flexion would therefore reduce strain in the saphenous nerve, most likely offsetting the possible impact of the increase in strain in the small infrapatellar branches. More research is however required to substantiate these assumptions.

Although substantial, compared to the longitudinal movement of other peripheral nerves, the magnitude of longitudinal excursion for the femoral nerve was relatively small. For example, the sciatic nerve in the mid-thigh moves (mean (SD)) 8.8 (3.5) mm with knee extension (Coppieters et al., 2015a,b), the tibial nerve at the popliteal fossa moves

Table 1
Mean (SD) for start and end position, and ROM for the knee and hip for knee flexion manoeuvres (Part A) and for the neck, knee and hip for Slump $_{\text{FEMORAL}}$ (Part B).

PART A	Knee movement			Hip control			
	Start	End	ROM	Start	End	ROM	*p*-value
Supine	2.7 (4.4)	132.7 (6.7)	129.9 (6.9)	−5.7 (3.4)	−5.7 (3.8)	0.0 (1.2)	0.14
Semi-seated	2.3 (5.0)	134.1 (5.8)	131.9 (6.9)	44.0 (3.4)	43.9 (3.5)	−0.1 (0.7)	0.46

PART B	Neck movement			Knee control				Hip control			
	Start	End	ROM	Start	End	ROM	*p*-value	Start	End	ROM	*p-value*
Slump $_{\text{FEMORAL}}$	15.1 (14.6)	109.1 (16.6)	94.0 (12.6)	118.7 (13.8)	118.8 (13.9)	- 0.1 (1.5)	0.75	− 2.3 (10.1)	− 2.1 (9.6)	0.1 (2.0)	0.48

For the knee, zero degrees refers to full knee extension; for the hip, negative values refer to hip extension; for the neck, positive values refer to flexion. *P*-values are reported for comparisons between start and end positions for joints that were controlled.

Table 2
Longitudinal and transverse (X,Y axis) excursion for the femoral nerve in supine and a semi-seated position and Slump $_{FEMORAL}$.

Position	Movement	Longitudinal Distal direction	Transverse	
			Medial direction (X-axis)	Superficial direction (Y-axis)
Supine	Knee flexion	3.6 (2.0) (2.9, 4.3) †	1.4 (0.3) (1.3, 1.5) †	0.2 (0.2) (−0.3, −0.2) †
Semi-seated	Knee flexion	1.1 (1.6) (0.5, 1.7) †	0.7 (0.1) (0.4, 0.9) †	0.1 (0.2) (−0.2, 0.0)
Slump $_{FEMORAL}$	Neck flexion	0.0 (0.3) (−0.1, 0.1)	1.1 (0.5) (0.9, 1.3) †	0.0 (0.1) (−0.0, 0.1)

*Values are mean (SD) mm (95% confidence interval).
†$p \le 0.01$.

12.2 (2.2) mm with hip and spinal flexion (Shum et al., 2013) and the median nerve moves 5.6 (2.1) mm in the upper arm (Coppieters et al., 2009) and 10.4 (2.3) mm in the forearm (Dilley et al., 2003) with elbow extension. It should be noted however that in all these studies the assessed nerve crossed the joint that was mobilised. To our knowledge, the present study is the only study in which the assessed peripheral nerve (i.e., femoral nerve) does not cross the joint (i.e., knee) that was mobilised.

For transverse excursion, the amount of movement was similar to other nerves (e.g., the median nerve at the wrist moves 0.4 mm posteriorly and 1.8 mm laterally with finger extension (Hough et al., 2007); the tibial nerve in the popliteal fossa moves 1.4 mm medially with dorsiflexion (Boyd et al., 2012)). Other studies reported variability between participants in the direction of transverse movement (e.g., for the sciatic nerve (Ellis et al., 2008; Ridehalgh et al., 2014) and median nerve (Hough et al., 2007)). In our study, the direction of transverse femoral nerve movement was consistently in the same direction, i.e., medial and anterior (superficial) direction.

Structural differentiation using remote joint movements is essential when attempting to identify femoral nerve or L2-L4 nerve roots pathology as possible anatomical sources of anterior thigh pain, and hip and knee pain. Although neck movements are typically advocated to assist in structural differentiation during Slump $_{FEMORAL}$, neck flexion in the end position of Slump $_{FEMORAL}$ did not result in further longitudinal excursion of the femoral nerve. Possibly, the end position of Slump $_{FEMORAL}$ was not sufficiently reached or neck flexion might have increased strain in the femoral nerve, rather than induced longitudinal nerve excursion. Unfortunately, localised strain measurements require invasive techniques that are not suitable for *in-vivo* studies. The fact that neck flexion may have an effect on the femoral nerve is supported by the observation of a medial movement of the femoral nerve following neck flexion. Movement in the same direction was observed when the bedding of the femoral nerve was lengthened with knee flexion. Invasive strain measurements (Gilbert et al., 2007; Lohman et al., 2015) or elastography *in vivo* (Andrade et al., 2016) are required to further investigate the effect of neck movement on the biomechanics of the femoral nerve in Slump $_{FEMORAL}$.

Although neck extension in the end position of Slump $_{FEMORAL}$ is more commonly advocated, sensitising manoeuvres that increase or decrease the length of the nerve bedding are both useful in differential diagnosing (Butler, 2000). The fact that we did not want to put the participants in a neuromechanically loaded position for too long was the main reason why we performed neck flexion rather than neck extension as a sensitising manoeuvre. We did not monitor or restrict movements of the pelvis, spine and hip during knee movements in the supine and semi-seated position. Although we attribute the differences in femoral nerve biomechanics to differences in the starting position, we cannot rule out that minor changes in pelvis, spine and hip position occurred during knee flexion. Although small movements of the pelvis and spine may be difficult to control in clinical settings during neurodynamic tests, future experimental studies may want to quantify these movements when evaluating nerve biomechanics.

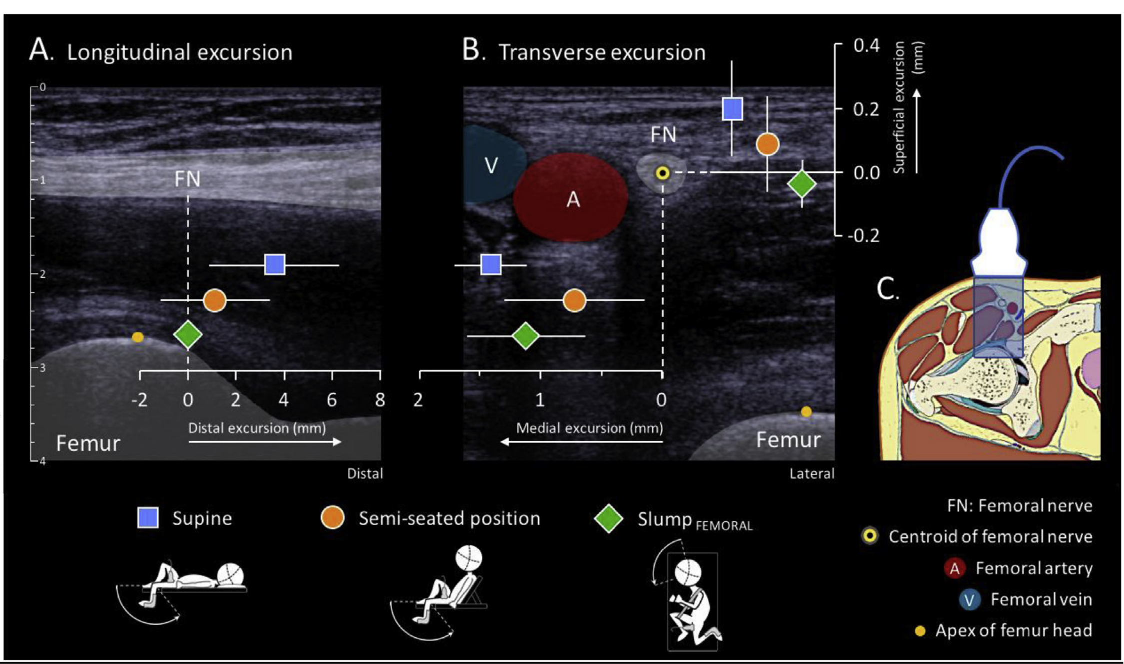

Fig. 2. Longitudinal (A) and transverse (B) excursion of the femoral nerve during knee flexion in supine and a semi-seated position, and during neck flexion in Slump $_{FEMORAL}$. Location of the ultrasound probe is also illustrated in a cross-sectional anatomical diagram (C). Values (mean (SD)) reflect femoral nerve movement adjusted for femur movement.

Pilot data suggested the usefulness of Slump $_{\text{FEMORAL}}$ as a clinical test to identify patients with mid lumbar nerve root compression (Trainor and Pinnington, 2011). Our results revealed that components of Slump $_{\text{FEMORAL}}$ and the Prone Knee Bend test indeed mechanically challenge the femoral nerve. Our findings are in line with the preliminary intra-operative data mentioned above (Kobayashi et al., 2003) and contribute to the biomechanical plausibility (validity) of neurodynamic tests for the femoral nerve. Future studies are required to reveal the diagnostic accuracy of these tests.

References

Andrade, R.J., Nordez, A., Hug, F., Ates, F., Coppieters, M.W., Pezarat-Correia, P., Freitas, S.R., 2016. Non-invasive assessment of sciatic nerve stiffness during human ankle motion using ultrasound shear wave elastography. J. Biomech. 49, 326–331.

Boyd, B.S., Gray, A.T., Dilley, A., Wanek, L., Topp, K.S., 2012. The pattern of tibial nerve excursion with active ankle dorsiflexion is different in older people with diabetes mellitus. Clin. Biomech. 27, 967–971.

Butler, D.S., 2000. The Sensitive Nervous System. Noigroup Publications, Adelaide, Australia.

Coppieters, M.W., Kurz, K., Mortensen, T.E., Richards, N.L., Skaret, I.A., McLaughlin, L.M., Hodges, P.W., 2005. The impact of neurodynamic testing on the perception of experimentally induced muscle pain. Man. Ther. 10 (1), 52–60.

Coppieters, M., Nee, R., 2015. Grieve's Modern Musculoskeletal Physiotherapy, fourth ed. Elsevier, China Chapter 30 Neurodynamic management of the peripheral nervous system.

Coppieters, M.W., Andersen, L.S., Johansen, R., Giskegjerde, P.K., Høivik, M., Vestre, S., Nee, R.J., 2015a. Excursion of the sciatic nerve during nerve mobilization exercises: an in vivo cross-sectional study using dynamic ultrasound imaging. J. Orthop. Sports Phys. Ther. 1–23.

Coppieters, M.W., Crooke, J.L., Lawrenson, P.R., Khoo, S.J., Skulstad, T., Bet-Or, Y., 2015b. A modified straight leg raise test to differentiate between sural nerve pathology and Achilles tendinopathy. A cross-sectional cadaver study. Man. Ther. 20 (4), 587–591.

Coppieters, M.W., Hough, A., Dilley, A., 2009. Different nerve-gliding exercises induce different magnitudes of median nerve longitudinal excursion: an in vivo study using dynamic ultrasound imaging. J. Orthop. Sports Phys. Ther. 39, 164–171.

Dilley, A., Greening, J., Lynn, B., Leary, R., Morris, V., 2001. The use of cross-correlation analysis between high-frequency ultrasound images to measure longitudinal median nerve movement. Ultrasound Med. Biol. 27, 1211–1218.

Dilley, A., Lynn, B., Greening, J., DeLeon, N., 2003. Quantitative in vivo studies of median nerve sliding in response to wrist, elbow, shoulder and neck movements. Clin. Biomech. 18, 899–907.

Ellis, R., Hing, W., Dilley, A., McNair, P., Cowin, D., Hall-Craggs, M., Al, E., 2008. Reliability of measuring sciatic and tibial nerve movement with diagnostic ultrasound during a neural mobilisation technique. Ultrasound Med. Biol. 34, 1209–1216.

Ellis, R., Osborne, S., Whitfield, J., Parmar, P., Hing, W., 2017 May. The effect of spinal position on sciatic nerve excursion during seated neural mobilisation exercises: an in vivo study using ultrasound imaging. J. Man. Manip. Ther. 25 (2), 98–-105. http://dx.doi.org/10.1179/2042618615Y.0000000020.

Fanara, B., Christophe, J.L., Boillot, A., Tatu, L., Jochum, D., Henri, Y., Berthier, F., Samain, E., 2014. Ultrasound guidance of needle tip position for femoral nerve blockade: an observational study. Eur. J. Anaesthesiol. 31 (1), 23–29. http://dx.doi.org/10.1097/01.EJA.0000435016.83813.aa.

Faul, F., Erdfelder, E., Lang, A.-G.A., Buchner, A., 2007. G*power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav. Res. Meth. 39, 175e91.

Gilbert, K.K., Brismée, J.M., Collins, D.L., James, C.R., Shah, R.V., Sawyer, S.F., Sizer, P.S., 2007. 2006 Young Investigator Award Winner: lumbosacral nerve root displacement and Strain. Part 2. A comparison of 2 straight leg raise conditions in unembalmed cadavers. Spine (Phila Pa 1976) 32, 1521–1525.

Gruber, H., Peer, S., Kovacs, P., Marth, R., Bodner, G., 2003. The ultrasonographic appearance of the femoral nerve and cases of iatrogenic impairment. J. Ultrasound Med. 22, 163–172.

Hough, A.D., Moore, A.P., Jones, M.P., 2007. Reduced longitudinal excursion of the median nerve in carpal tunnel syndrome. Arch. Phys. Med. Rehabil. 88 (5), 569–576.

Kasehagen, B., Ellis, R., Pope, R., Russell, N., Hing, W., 2018. Assessing the reliability of ultrasound imaging to examine peripheral nerve excursion: a systematic literature review. Ultrasound Med. Biol. 44 (1), 1–13. http://dx.doi.org/10.1016/j.ultrasmedbio.2017.08.1886.

Kobayashi, S., Suzuki, Y., Asai, T., Yoshizawa, H., 2003. Changes in nerve root motion and intraradicular blood flow during intraoperative femoral nerve stretch test. Report of four cases. J. Neurosurg. 99, 298–305.

Lohman, C.M., Gilbert, K.K., Sobczak, S., Brismée, J.-M., James, C.R., Day, M., Smith, M.P., Taylor, L., Dugailly, P.-M., Pendergrass, T., Sizer, P.J., 2015. 2015 young investigator award winner. Spine (Phila Pa 1976) 40, 793–800.

Nee, R.J., Jull, G.A., Vicenzino, B., Coppieters, M.W., 2012. The validity of upper-limb neurodynamic tests for detecting peripheral neuropathic pain. J. Orthop. Sports Phys. Ther. 42, 413–424.

Rade, M., Pesonen, J., Könönen, M., Marttila, J., Shacklock, M., Vanninen, R., Kankaanpää, M., Airaksinen, O., 2017. Reduced spinal cord movement with the straight leg raise test in patients with lumbar intervertebral disc herniation. Spine (Phila Pa 1976) 42, 1117–1124.

Ridehalgh, C., Moore, A., Hough, A., 2014. Normative sciatic nerve excursion during a modified straight leg raise test. Man. Ther. 19, 59–64.

Ridehalgh, C., Moore, A., Hough, A., 2015. Sciatic nerve excursion during a modified passive straight leg raise test in asymptomatic participants and participants with spinally referred leg pain. Man. Ther. 20, 564–569.

Shacklock, M., Yee, B., Van Hoof, T., Foley, R., Boddie, K., Lacey, E., Poley, J.B., Rade, M., Kankaanpää, M., Kröger, H., Airaksinen, O., 2016. Slump test: effect of contralateral knee extension on response sensations in asymptomatic subjects and cadaver study. Spine (Phila Pa 1976) 41, E205–E210.

Shum, G.L., Attenborough, A.S., Marsden, J.F., Hough, A.D., 2013. Tibial nerve excursion during lumbar spine and hip flexion measured with diagnostic ultrasound. Ultrasound Med. Biol. 39, 784–790.

Szucs, S., Morau, D., Iohom, G., 2010. Femoral nerve blockade. Med. Ultrason. 12 (2), 139–144.

Trainor, K., Pinnington, M.A., 2011. Reliability and diagnostic validity of the slump knee bend neurodynamic test for upper/mid lumbar nerve root compression: a pilot study. Physiotherapy 97, 59–64.

Weir, J.P., 2005. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J. Strength Condit Res. 19, 231.